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What Did They Do in IEA 34/43? Or How to Diagnose and Repair Bugs in 500,000 Lines of Code

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R. Judkoff
National Renewable Energy Laboratory

J. Neymark
J. Neymark & Associates

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WHAT DID THEY DO IN IEA 34/43?

OR HOW TO DIAGNOSE AND REPAIR BUGS IN 500,000 LINES OF CODE

Ron Judkoff[1] and Joel Neymark[2]

[1]National Renewable Energy Laboratory, Golden, Colorado, USA[a]

[2]Neymark and Associates, Golden, Colorado, USA

ABSTRACT

This paper presents an overview of the recently completed International Energy Agency Solar Heating and Cooling Task 34 and Energy Conservation in Buildings and Community Systems Annex 43 (IEA 34/43) on Testing and Validation of Building Energy Simulation Tools. The paper includes discussion of the technical and historical context, methodology, organization, accomplishments, and adoption by standards organizations and other regulatory entities.

INTRODUCTION

Modern whole-building energy simulation software may contain on the order of a half million lines of code. It is therefore helpful to develop testing and diagnostic methods that identify errors and indicate where in the code those errors are to facilitate corrections. The National Renewable Energy Laboratory (NREL) and the IEA have maintained a validation effort related to building energy simulation software since the first ECBCS project, Annex 1, which ran from 1977 to 1980 (ECBCS News, October 2007). Follow-on validation work was done in the IEA Solar Heating and Cooling Programme (SHC) Task 8, SHC Task 12/ECBCS Annex 21, and SHC Task 22. The most recent work was conducted under a combined effort of IEA SHC Task 34 and ECBCS Annex 43. The work began in June 2002 and was formally completed in December 2007. In all, 53 experts from 32 organizations and 13 countries contributed significantly to the Task in 6 project areas. These included A) Building to ground heat transfer B1) Multi-zone effects, not including airflow B2) Multi-zone airflow effects C) Shading, daylighting, and load interactions D) Hydronic heating and cooling systems, and E) Double-skin facades. The tests developed under these projects included empirical, comparative, and analytical solution-based methods, all of which are integral parts of the overall NREL/IEA/ASHRAE validation methodology, sometimes called BESTEST.

A new method based on stand-alone numerical solutions was developed that extends the analytical solution approach such that it can be applied to more realistic and less constrained test cases. The empirical validation work involved the construction and use of some unique test facilities designed expressly for the purpose of model validation. These included a double-façade test facility at Aalborg University in Denmark, Test Cells at EMPA in Switzerland, a test building at the Iowa Energy Center in the United States, and laboratory tests at the Technical University of Dresden in Germany. Participants in the Task either developed test suites or subjected building energy simulation software to the tests, or both, in an iterative process that facilitated the improvement of the test case specifications and the software. Each of the 6 full-length technical reports that resulted from the work describes the specifications for the tests in enough detail that an independent software producer or software user could perform the tests. In addition, these documents discuss the results from the models that were tested, the experiences of those who performed the tests, and improvements to software from the testing. Overall, 24 of the world's leading building simulation models were tested, resulting in more than 100 identified bugs and about 80 software corrections and/or improvements.

THEORY

There are three ways to evaluate a whole-building energy simulation program's accuracy (Judkoff et al. 1983/2008; Judkoff and Neymark 2006):

- *Empirical validation*, which compares calculated results from a program, subroutine, algorithm, or software object to monitored data from a real building, test cell, or laboratory experiment

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- *Analytical verification*, which compares outputs from a program, subroutine, algorithm, or software object to results from a known analytical solution or to results from a set of closely agreeing quasi-analytical solutions or verified numerical models
- *Comparative testing*, which compares a program to itself or to other programs. Table 1 compares these techniques (Judkoff et al. 1983/2008; Judkoff 1988; Judkoff and Neymark 2006). In this table, the term *model* is the representation of reality for a given physical behavior. For example, heat transfer may be simulated with one-, two-, or three-dimensional thermal conduction models. The term *solution process* encompasses the mathematics and computer coding to solve a given model. The solution process for a model can be perfect, even though the model remains inappropriate for a given physical situation, such as using a one-dimensional conduction model where two-dimensional conduction dominates. The term *truth standard* represents the standard of accuracy for predicting real behavior. An analytical solution is a "mathematical truth standard," and tests the solution process for a model, but not the appropriateness of the model. An approximate truth standard from an experiment tests both the solution process and appropriateness of the model within experimental uncertainty. The ultimate validation truth standard would be comparison of simulation results with a perfectly performed empirical experiment, with all simulation inputs perfectly defined.

Table 1
Validation Techniques

TECHNIQUE	ADVANTAGES	DISADVANTAGES
Empirical Validation Test of model and solution process	• Approximate truth standard within experimental accuracy • Any level of complexity	• Experimental uncertainties: - Instrument calibration, and spatial/temporal discretization - Imperfect knowledge/ specification of experimental object (building) being simulated • High-quality, detailed measurements are expensive and time-consuming • Only a limited number of test conditions are practical
Analytical Verification Test of solution process	• No input uncertainty • Exact mathematical or secondary mathematical truth standard for given model • Inexpensive	• No test of model validity • Limited to highly constrained cases for which analytical or quasi-analytical solutions can be developed
Comparative Testing Relative test of model and solution process	• No input uncertainty • Any level of complexity • Many diagnostic comparisons possible • Inexpensive and quick	No absolute truth standard (only statistically based acceptance ranges are possible)

Source: Judkoff and Neymark 2006.

Table 1 shows that each validation technique has different strengths and weaknesses. In practice it is very expensive to empirically validate objects of the scale and complexity of buildings. This limits high-quality empirical validation data to a very few cases and therefore limits the diagnostic power of the cases (we discuss high-quality validation data toward the end of this section). By combining empirical, analytical, and comparative validation techniques, we can compensate for the weaknesses in any individual technique.

A comparison between measured and calculated performance represents a small region in an immense *N*-dimensional parameter space. Investigators are constrained to exploring relatively few domains in this space, yet would like to be assured that the results are not coincidental (e.g., not a result of offsetting errors) and do represent the validity of the simulation elsewhere in the parameter space. Analytical and comparative techniques minimize the uncertainty of extrapolations around the limited number of sampled empirical domains. Table 2 classifies these extrapolations. Use of the term *vice versa* in Table 2 is intended to mean that the extrapolation can go both ways (e.g., from short-term to long-term data and from long-term to short-term data). This does not mean that such extrapolations are correct, but only that researchers and practitioners have either explicitly or implicitly made such inferences in the past.

Figure 1 shows one process to combine analytical, empirical, and comparative techniques. These three techniques may also be used together in other ways; for example, intermodel comparisons may be done before an empirical validation exercise, to better define the experiment and to help estimate experimental uncertainty by propagating all known error sources through one or more whole-building energy simulation programs (Hunn et al. 1982; Lomas et al. 1994).

Table 2
Types of Extrapolation

OBTAINABLE DATA POINTS	EXTRAPOLATION
A few climates	Many climates
Short-term total energy use	Long-term total energy use, or vice versa
Short-term (hourly) temperatures and/or fluxes	Long-term total energy use, or vice versa
A few equipment performance points	Many equipment performance points
A few buildings representing a few sets of variable and parameter combinations	Many buildings representing many sets of variable and parameter combinations, or vice versa
Small-scale: simple test cells, buildings, and mechanical systems; laboratory experiments	Large-scale complex buildings with complex HVAC systems, or vice versa

Source: Neymark and Judkoff 2002

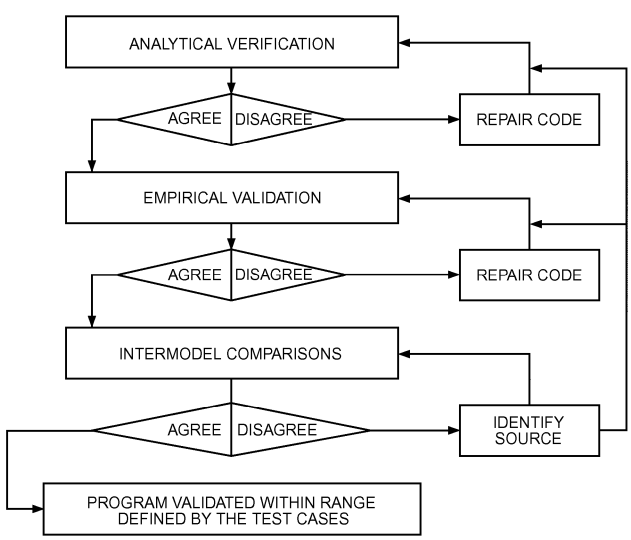

Figure 1 Validation Method

(Judkoff and Neymark 2006)

For the path shown in Figure 1, there are three steps:

1. Run the code against analytical verification test cases to check its mathematical solution. Discrepancies must be corrected before proceeding further.
2. Run the code against high-quality empirical validation data and correct any errors .
3. Check the agreement of several programs with different thermal solution and modeling approaches (that have passed through steps 1 and 2) in a variety of representative cases. This uses the comparative technique as an extrapolation tool. Deviations in the program predictions indicate areas for further investigation.

When programs successfully complete these three stages, they are considered validated for cases where acceptable agreement was achieved (i.e., for the range of building, climate, and mechanical system types represented by the test cases). Once several detailed simulation programs have satisfactorily completed the procedure, other programs and simplified design tools can be tested against them. A validated code does not necessarily represent truth. It does represent a set of algorithms that have been shown, through a repeatable procedure, to perform according to the current state of the art.

The NREL methodology for validating building energy simulation programs has been generally accepted by the International Energy Agency (Irving 1988), ASHRAE *Standard* 140 and Addendum p to ASHRAE *Standard* 90.1, and elsewhere.

We are frequently asked why high-quality empirical validation is so difficult? The simplest level of empirical validation compares a building's long-term energy use to that calculated by a computer program, and in principle, any building with a meter could be used. Unfortunately, it is impossible to interpret the results of such an exercise because all possible sources of error are acting simultaneously. Even if good agreement between measured and calculated energy consumption is observed, possible offsetting errors prevent a definitive conclusion about a model's accuracy. More informative levels of empirical validation involve controlling known sources of error to identify and quantify unknown error sources and to reveal causal relationships associated with error sources. These error sources may be separated into two groups.

External Error Types:

- Differences between actual building microclimate versus the weather input to the computer program
- Differences between actual schedules, control strategies, effects of occupant behavior, and other effects from the real building versus those assumed by the program user
- User error deriving building input files
- Differences between actual physical properties of the building (including HVAC systems) versus those input by the user.

Internal Error Types:

- Differences between actual thermal transfer mechanisms in the real building and its HVAC systems versus the simplified model of those processes in the simulation (all models, no matter how detailed, are simplifications of reality)
- Errors or inaccuracies in the mathematical solution of the models
- Coding errors.

Designing and conducting validation experiments that allow control or isolation of these various error sources is challenging and expensive, but not impossible. The best validation experiments are from test cells or buildings constructed specifically for the purposes of model validation. Some of these facilities have features such as movable thermal guard zones, the ability to cut off difficult-to-measure heat transfer paths, and detailing to minimize two- and three-dimensional conduction. Overall, it is best to design a test facility that can emulate the simplifying assumptions in the models, and then allow more realistic heat flows to be activated one at a time. In general, the more realistic the test building, the more difficult it is to establish causality and diagnose problems; the simpler and more controlled the test case, the easier it is to pinpoint sources of error or inaccuracy.

TASK 34/43

The objective of *SHC Task 34/ECBCS Annex 43: Testing and Validation of Building Energy Simulation Tools* was to undertake pre-normative research to continue to develop a comprehensive and integrated suite of building energy analysis tool tests that can provide software quality assurance. The parameter space within which building energy simulation software operates can be visualized by the matrix in Table 3 (Judkoff 2008). Each cell in the table represents an extremely large portion of the parameter space. IEA 34/43 sought to add tests to several of these cells as follows.

Comparative tests developed within IEA 34/43 included:

- BESTEST ground-coupled heat transfer with respect to floor slab construction (Project A)
- BESTEST multi-zone heat transfer, shading, and internal windows (Project B1)
- BESTEST airflow, including multi-zone airflow (Project B2)
- Chilled-water and hot-water mechanical systems and components (Project D)
- Buildings with double-skin façades (Project E3).

Within the comparative test cases, analytical verification tests for evaluating basic heat transfer and mathematical processes in building energy analysis tools were included where possible.

Empirical validation tests developed within IEA 34/43 included:

- Shading/daylighting/load interaction (Project C)
- Chilled-water and hot-water mechanical systems and components (Project D)
- Buildings with double-skin facades (Project E2).

Work on double-skin façades also included a comprehensive literature survey on double-skin façade buildings (Project E1).

To effectively disseminate the results of the Annex, a single web site (Project G) will consolidate IEA tool evaluation tests from SHC Task 12/ECBCS Annex 21, SHC Task 22, and SHC Task 34/ ECBCS Annex 43, and other ECBCS and SHC research tasks. This web site should be ready in the latter half of 2009.

Results

SHC Task 34/ECBCS Annex 43 had 53 participants from 32 organizations in the following 14 countries: Australia, Belgium, Canada, Denmark, France, Germany, Ireland, Japan, Kuwait, the Netherlands, Sweden, Switzerland, the United Kingdom, and the United States. Twenty-four computer programs/models were tested, as shown in Table 4. The participants expended more than 33 person-years (400 person-months) of effort over the course of the task, primarily to develop test specifications, gather empirical data, run simulations and generate the final reports.

SOFTWARE IMPROVEMENTS

This work has led to direct improvements in software tools used for evaluating the impacts of energy efficiency and solar energy technologies commonly applied in innovative low-energy buildings. During the field trials of the new test procedures, 106 results disagreements were identified, which led to 80 software fixes, including model and documentation improvements (other fixes are being worked on). Table 5 indicates by project the number of model errors that were identified and fixed so far. This indicates the utility of empirical validation (Projects C, D, and E), and analytical verification and comparative testing (Projects A and B) to identify disagreements that lead to corrections. Accuracy improvements in simulation models, demonstrated here and in previous IEA work, have increased confidence in model use by architects and engineers who rely on building energy simulation tool calculations to perform their work.

Table 3
IEA Validation Test Matrix

	BUILDING FABRIC	HVAC	ON-SITE GENERATION EQUIPMENT
Analytical Verification	• Slab-on-grade ground-couple (US) • Airflow and multi-zone air (Japan) • Working document of Analytical Tests (Finland)	• HVAC BESTEST vol. 1 (US) • HVAC BESTEST, fuel-fired furnace (Canada)	
Comparative Tests and Diagnostics	• Envelope BESTEST (US) • Expanded ground coupling test cases (US) • Multi-Zone Non-Airflow (US) • Double-Façade Working Document (Denmark)	• HVAC BESTEST vol. 2 (US) • RADTEST, radiant heating (Switzerland) • Hydronic Systems (Germany)	• Residential Cogeneration (Canada)
Empirical Validation	• ETNA/GENEC Tests (France) • BRE/DMU Tests (UK) • EMPA Shading/Cooling (Switzerland) • ERS Daylighting/HVAC 2 (US) • AAU Double-Façade Tests (Denmark)	• ERS VAV HVAC (US) • ERS Daylighting/HVAC I (US) • ERS Economizer Control (US) • TUD/ERS Hydronic Systems (Germany)	• Residential Cogeneration (Canada)

(test suite lead country in parentheses)

Table 4
Models Tested during IEA SHC Task 34/ECBCS Annex 43

MODEL TESTED	PARTICIPATING COUNTRY	PROJECT
BASECALC	Canada	A
BSim	Denmark	E
CODYRUN	France	B1 (MZ320 only),B2
COMFIE	France	B1 (MZ320 only)
COMIS 3.2	Japan	B2
DOE-2.1E	Switzerland	C
EES	Belgium	D
EnergyPlus	Switzerland	C
EnergyPlus	United States	A, B1, B2, D
ESP-r	United Kingdom	B1, B2, C, E
ESP-r/BASESIMP	Canada	A
FLUENT*	Kuwait	A
HELIOS	Switzerland	C
HTB2	United Kingdom	B1, B2
IDA-ICE	Sweden	E
IDA-ICE	Switzerland	C
KoZiBu	France	B1 (MZ320 only)
MATLAB*	Ireland	A
MATLAB-Simulink	Germany	D
SUNREL-GC/GHT	United States	A
TRNSYS-TUD	Germany	B1, B2, C, D, E
TRNSYS-16*	United States	A
TRNSYS-16	Belgium	B1, C
VA114	Netherlands	B1, D, E
VA114/ISO-13370	Netherlands	A
VentSim	Japan	B2

* Used as platform for developing detailed 3-D numerical model

Project A also developed a new formal methodology to facilitate using and verifying numerical models to develop quasi-analytical solutions. This allows for greatly enhanced diagnostic capability when comparing results of other simplified and mid-level-detailed modeling methods that are typically used with whole-building energy simulation programs. Diagnostics are enhanced because the range of disagreement between quasi-analytical solutions for specific thermal mechanisms is typically much narrower than that between whole-building simulations. The methodology improvement also allows quasi-analytical solutions to be developed for more realistic (less constrained) cases than is possible for exact analytical solutions.

Table 5
Model Fixes Attributable to IEA SHC 34 / ECBCS Annex 43

PROJECT	**LEADER**	**DISAGREEMENTS**		**MODELS**
		Fixed	**Identified**	**Tested**
A. Ground Coupled Slab-on-Grade,	U.S./NREL	19	24	9
B1. Multi-Zone Non-Airflow	U.S./NREL	32	48	9
B2. Airflow	Japan	1	1	7
C. Shading/Daylighting/Load Interaction	Switzerland, U.S./Iowa	14	14	7
D. Mechanical Equipment and Controls	Germany	8	10	5
E2. Double-Skin Facade	Denmark	6	9	5
IEA SHC 34/ ECBCS 43 TOTAL		80	106	24*

* Many models were tested in multiple projects as shown in Table 4

RESEARCH DISSEMINATION

The test procedures and final reports published by SHC Task 34/ECBCS Annex 43, summarized in Table 6, are posted at [www.iea-shc.org/publications/task. aspx?Task=34](www.iea-shc.org/publications/task.aspx?Task=34). The participants have also published more than 20 conference papers and journal articles. Several more papers were developed for a special invited session on Annex 43 for the Building Simulation 2009 conference in Glasgow, UK, July 27-30, 2009, organized by the International Building Performance Simulation Association.

Table 6
Summary of Reports Developed in Annex 43

PROJECT/TITLE	**LEAD AUTHORS**	**LEAD COUNTRY**
A. IEA BESTEST In-Depth Diagnostic Cases for Ground Coupled Heat Transfer Related to Slab-on-Grade Construction	J. Neymark, R. Judkoff	United States
B1. IEA BESTEST Multi-Zone Non-Airflow In-Depth Diagnostic Cases: MZ320 – MZ360	J. Neymark, R. Judkoff	United States
B2. Airflow Tests Including Multi-Zone Airflow	Y. Utsumi, T. Mitamura	Japan
C. Empirical Validations of Shading/Daylighting/Load Interactions in Building Energy Simulation Tools	P. Loutzenhiser, H. Manz, G. Maxwell	Switzerland, United States
D. Mechanical Equipment & Control Strategies for a Chilled Water and a Hot Water System	C. Felsmann	Germany
E1. Double Skin Facades, a literature review	H. Poirazis	Sweden
E2. Empirical Validation of Building Simulation Software: Modeling of Double Facades	O. Kalyanova, P. Heiselberg	Denmark

Sources: Felsmann 2008; Loutzenhiser 2007; Neymark et al. 2008a, 2008b; Poirazis 2006

INDUSTRY USE OF BESTEST

National and international building energy standards organizations have used test cases developed in this Task and earlier ECBCS and SHC tasks to create standard methods of tests for building energy analysis tools. An example is ANSI/ASHRAE Standard 140, *Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs* which is used in the US for national building energy code compliance. The impact of such work is apparent from the following:

- Standard 140 is referenced by:

- ASHRAE's commercial and non-low-rise residential building energy efficiency standard (ASHRAE Standard 90.1)
  - The US tax code for certifying software used to evaluate energy efficiency tax credits.
- Several European Union countries, as part of the building energy performance assessments under the European Community's Energy Performance Directive, use software tools that have been checked with IEA BESTEST.
- CEN used IEA BESTEST to check its reference cooling load calculation general criteria.
- Australia and New Zealand referenced IEA BESTEST in their codes and standards.
- *The 2005 ASHRAE Handbook of Fundamentals* section on validation references the IEA validation work.
- Researchers translated previous IEA BESTEST work into Dutch, German, and Japanese.
- A study comparing 20 whole-building energy simulation tools (Crawley et al. 2005) indicated that 19 of the 20 tools reviewed had been tested with at least one IEA BESTEST procedure; 10 tools had been tested with more than one BESTEST procedure. The study also indicated that test procedures developed by the ECBCS and SHC Programmes dominated the set of available tests.
- Major international commercial equipment providers such as Carrier Corp. (HAP) and Trane Company (TRACE) are using BESTEST/ Standard 140 for testing their software
- Many BESTEST suites have been directly integrated within ESP-r (an advanced simulation tool developed by the University of Strathclyde, and well known in Europe and Canada) for automated testing of revisions to the software.
- EnergyPlus, the U.S. Department of Energy's most advanced simulation program for building energy analysis, maintains its Standard 140 results on a web site.

There is a several year time lag between the development of new test suites and their incorporation into ASHRAE standards because of the ANSI/ASHRAE consensus standards process. Future revisions of Standard 140 will consider adaptation of additional test suites, including those recently developed under IEA 34/43. The project committee that oversees Standard 140 (SSPC 140) includes 9 voting members representing software developers and users, and is chaired by Ron Judkoff of NREL.

RECOMMENDATIONS AND CONCLUSIONS

As a result of SHC Task 34/ECBCS Annex 43, the content of the IEA Tool Evaluation Test Matrix has been augmented as shown in Table 3. This table also includes test procedures developed under SHC Task 12/ECBCS Annex 21, ECBCS Annex 42, and SHC Tasks 8 and 22. Although this represents a useful suite of basic tests, it does not address a broad enough cross-section of topics to represent a comprehensive evaluation of building energy analysis tools. Additional work should focus on filling missing or only partially covered areas of the matrix in Table 3.

Building energy simulation software must constantly be augmented to keep pace with new technology development. Thus, there is always a need for validation. A continuation of the validation work is recommended by the IEA 34/43 experts; additional tests could include, but are not limited to, those for models of the following:

- More HVAC system configurations
- More realistic building/ground-coupled heat transfer
- Model calibration methods for existing buildings (for predicting retrofit energy savings)
- Active solar thermal systems
- Thermo-chemical systems.

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